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## Evaluation of a Disposable Diesel Exhaust Filter for Permissible Mining Machines

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U.S. BUREAU OF MINES  
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UNITED STATES DEPARTMENT OF THE INTERIOR



BUREAU OF MINES

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*Cover Photograph: Miner installing disposable diesel exhaust filter on permissible mining machine.*

**Report of Investigations 9508**

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**UNITED STATES DEPARTMENT OF THE INTERIOR  
Bruce Babbitt, Secretary**

**BUREAU OF MINES**

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### UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	kW	kilowatt
°C	degree Celsius	L/min	liter per minute
ft	foot	m	meter
ft <sup>2</sup>	square foot	m <sup>2</sup>	square meter
h	hour	mg/m <sup>3</sup>	milligram per cubic meter
hp	horsepower	mm	millimeter
in	inch	μm	micrometer
kg/shift	kilogram per shift	pct	percent

# EVALUATION OF A DISPOSABLE DIESEL EXHAUST FILTER FOR PERMISSIBLE MINING MACHINES

By J. L. Ambs,<sup>1</sup> B. K. Cantrell,<sup>2</sup> W. F. Watts, Jr.,<sup>3</sup> and K. S. Olson<sup>4</sup>

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## ABSTRACT

The U.S. Bureau of Mines (USBM) Diesel Research Program emphasizes the development and evaluation of emission control devices to reduce exposure of miners to diesel exhaust pollutants. Studies by the USBM have shown that diesel exhaust aerosol (DEA) contributes a substantial portion of the respirable aerosol in underground coal mines using diesel equipment not equipped with emission controls.

The USBM and the Donaldson Co., Inc., Minneapolis, MN, have developed a low-temperature, disposable diesel exhaust filter (DDEF) for use on permissible diesel haulage vehicles equipped with waterbath exhaust conditioners. These were evaluated in three underground mines to determine their effectiveness in reducing DEA concentrations.

The DDEF reduced DEA concentrations from 70 to 90 pct at these mines. The usable life of the filter ranged from 10 to 32 h, depending on factors that affect DEA output, such as mine altitude, engine type, and duty-cycle. Cost per filter is approximately \$40.

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## INTRODUCTION

Diesel equipment is gaining popularity in underground coal mines. There are about 2,234 units of diesel equipment in 164 underground coal mines compared to 1,374 units in 111 mines 5 years ago (1).<sup>5</sup> This increased use is due to the recognition that diesel-powered vehicles are more versatile, which can contribute to increased productivity compared with their electrically powered counterparts. Roughly, 33 pct of the diesel units haul coal, 45 pct haul miners and materials, and 22 pct do other duties such as roof bolting, rock dusting, and road maintenance.

A miner working in an underground coal mine using diesel equipment can be exposed to a wide array of pollutants emitted in the diesel exhaust. These include carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, sulfur dioxide, DEA, and a variety of hydrocarbon compounds. DEA consists mainly of carbonaceous soot, sulfates, trace metals, and adsorbed or condensed soluble organic compounds (2). Among these pollutants, DEA is of particular concern because it is almost entirely respirable in size, with more than 90 pct of the particles by mass, having an aerodynamic diameter less than 1.0  $\mu\text{m}$ . DEA is currently regulated under the 2.0  $\text{mg}/\text{m}^3$  respirable coal mine dust standard. A quantitative definition of the health risk resulting from these exposures remains

elusive, but during the past several years progress has been made in defining the problem.

Results from epidemiological studies, animal inhalation studies, and in vitro studies have provided sufficient data for National Institute for Occupational Safety and Health (NIOSH) to recommend that "whole diesel exhaust be regarded as a potential occupational carcinogen." NIOSH further stated that although this excess risk of cancer has not been quantitatively estimated, it is logical to assume that reduction in exposure to diesel exhaust would reduce the excess risk (3). In addition, the International Agency for Research on Cancer has declared that "... diesel engine exhaust is *probably carcinogenic to humans*" (4).

As a result of concern over exposure to DEA in the mine environment, Mine Safety and Health Administration (MSHA) published an advance notice of proposed rule-making to establish a permissible exposure limit for diesel particulate matter (5). A regulation limiting DEA levels underground could affect productivity and competitiveness, as well as the health and safety of mine workers. The USBM is working to reduce DEA exposure in mines by developing new, cost-effective, control technology. One such device is the DDEF (6).

## DISPOSABLE DIESEL EXHAUST FILTER

The USBM collaborated with Donaldson Company, Inc., to develop and test a DDEF for permissible diesel vehicles similar to the coal haulage vehicle shown in figure 1. Coal haulage vehicles are the primary sources of DEA in the coal mine atmosphere (7) and have special safety requirements (8) that affect the use of exhaust filters. The most important constraints are the requirements to limit exhaust temperature to 77° C and to eliminate flames and sparks from the engine exhaust. The waterbath exhaust conditioner (waterbath scrubber) is currently used for the dual purpose of cooling the exhaust and quenching flames and sparks while simultaneously maintaining acceptable engine backpressure. The safe and proper operation of the DDEF system for permissible vehicles is predicated upon the low-exhaust gas temperatures exiting the waterbath exhaust conditioner.

The DDEF system (figure 2), which meets the requirements of and has been approved under 30 CFR Part 36, consists of a water trap, filter element, filter housing, and exhaust backpressure indicator. The water trap is bolted directly to the outlet of the waterbath scrubber and

prevents water droplets from reaching the filter. If the filter becomes saturated with water, the backpressure increases rapidly, reducing the life of the filter. Water, in its vapor phase, will pass through a filter without any adverse effect on filter life or effectiveness. However, water droplets will not pass through the filter; they are absorbed by the filter media causing it to become saturated with water. This rapidly restricts the flow of exhaust gas through the filter resulting in a reduction in the life of the filter element. After the exhaust exits the water trap, it passes through the DDEF. The filter is similar to intake air filters used by large on-highway diesel vehicles. The configuration used in this project is a cone-shaped, 61-cm-long (24-in) filter with 270 5-cm (2-in) pleats and a filter area of 17  $\text{m}^2$  (180  $\text{ft}^2$ ). Other filter designs that will reduce cost and improve performance are under investigation.

The DDEF system was initially installed and tested on a Jeffrey<sup>6</sup> 4114 Ramcar manufactured by Dresser Industries, Inc. A simplified schematic of the Jeffrey 4114 waterbath scrubber, water makeup, and safety shutdown system is shown in figure 3. During normal operation,

<sup>5</sup>Italic numbers in parentheses refer to items in the list of references at the end of this report.

<sup>6</sup>Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.



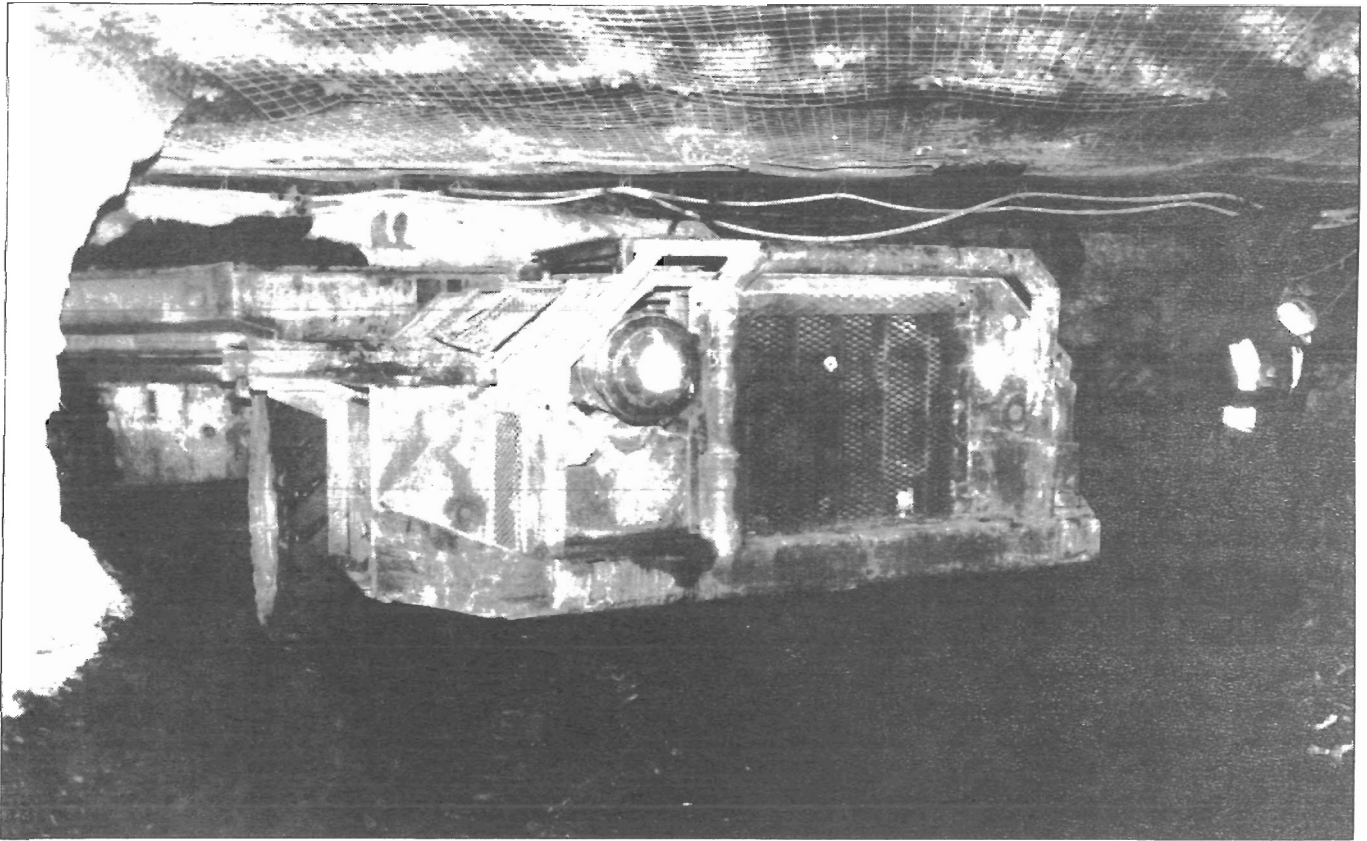


Figure 1.—Jeffrey 4114 Ramcar with disposable diesel exhaust filter installed.

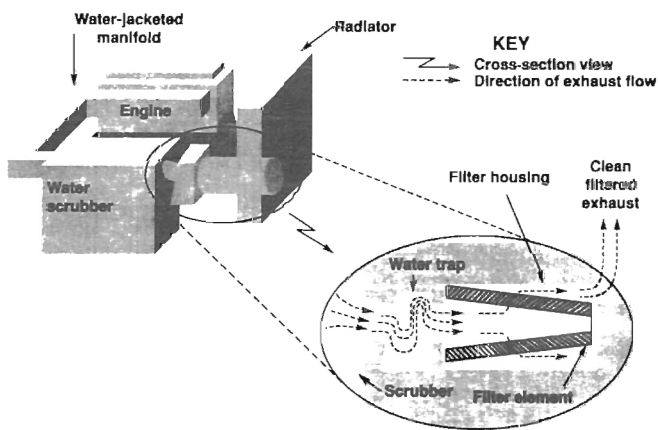


Figure 2.—Disposable diesel exhaust filter system.

pressurized water is fed from the make-up tank, through the low water shutdown tank, to the pilot valve. When the water level control float senses a low-water level within the waterbath scrubber, it activates the pilot valve allowing the pressurized water to enter the waterbath. When the water

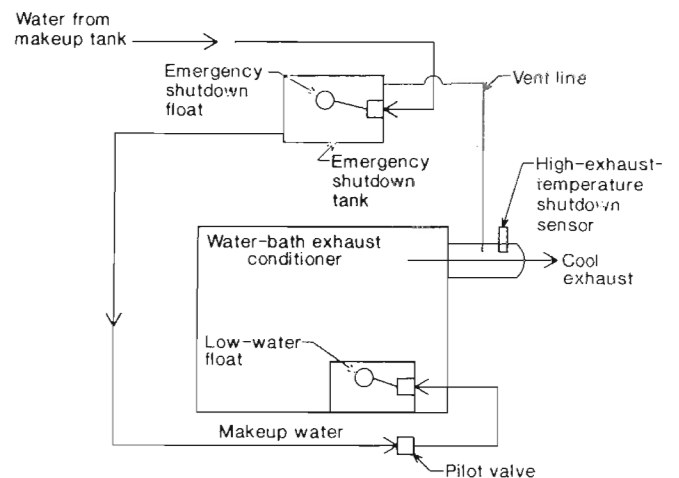


Figure 3.—Simplified schematic of Jeffrey 4114 makeup water and shutdown system.

within the make-up tank is depleted, the water remaining in the low water shutdown tank drains to the waterbath scrubber by gravity feed. This activates the low water

shutdown float, activating the emergency shutdown system on the vehicle and stopping the engine.

Initially, the addition of the DDEF system onto the Jeffrey 4114 Ramcar adversely affected the operation of the waterbath scrubber and safety shutdown system. Design modifications were made to the vehicle to correct the problems.

### FIELD EVALUATION OF DISPOSABLE DIESEL EXHAUST FILTER

The collection efficiency and life expectancy of the DDEF system were evaluated during week-long field studies at three mines.

Aerosol data were collected in continuous miner sections of these underground coal mines while the diesel haulage vehicles were equipped with and without the DDEF installed. These mines are designated M, R, and S. Mine M was located in Utah at an altitude of approximately 2,400 m (8,000 ft). Mine R was located in Alabama and mine S in Kentucky. Each mine produces high volatile, bituminous coal with shift production levels varying from 272 to 604 kg/shift. Seam heights varied from 1.5 to 2.4 m. Mines M and R use continuous mining to develop longwall panels. Mine S is a room-and-pillar operation that uses a continuous miner.

Mines R and S operated three to four Jeffrey 4110 Ramcars in the test section. The Jeffrey 4110 Ramcars were equipped with Motorenwerke Mannheim (MWM) D916-6 engines, rated at 74.6 kW (100 hp). Mine M used three to four Jeffrey 4114 Ramcars powered by Caterpillar 3306 PCNA engines. These engines were derated for high altitude operation from 111.9 to 82.1 kW (150 to 110 hp). At the first mine, the Ramcars were operated for 4 days with the DDEF installed and for 1 day without the DDEF installed. At the other two mines, the Ramcars were operated for 3 days with the DDEF and for 2 days without.

### SAMPLING AND ANALYSIS METHODS

It was shown in the laboratory (9), and in underground mines (10-12), that inertial impaction, followed by gravimetric analysis, can be used to separate and sample DEA and mineral dust aerosol fractions, and provide estimates of DEA concentrations. Two types of personal diesel exhaust aerosol samplers (PDEAS) were developed to

achieve this result and are depicted in figure 4 (13-14). Both have three stages and employ inertial impaction to separate diesel and mineral dust fractions of the sampled respirable aerosol. The first stage is an inertial pre-classifier, a 10-mm-Dorr-Oliver cyclone that separates and removes the larger, nonrespirable aerosol. The second stage is a four-nozzle impactor with a sharp 50 pct cut point of  $0.8\ \mu\text{m}$  aerodynamic diameter. Most aerosol particles larger than  $0.8\ \mu\text{m}$ , the respirable coal dust, are deposited on an impaction substrate in this stage. The third stage is a filter which collects the remaining aerosol of less than  $0.8\ \mu\text{m}$  aerodynamic diameter, the DEA. Both samplers operate at a flow rate of 2 L/min, which is compatible with both personal sampler pumps and the Dorr-Oliver cyclone.

Preliminary evaluations of the sampling technique indicate that these are accurate to within 25 pct, 95 pct of the time, for concentration levels above the estimated limit of detection of  $0.3\ \text{mg}/\text{m}^3$ . Below this level, indications are that the 95 pct confidence interval can exceed 60 pct due

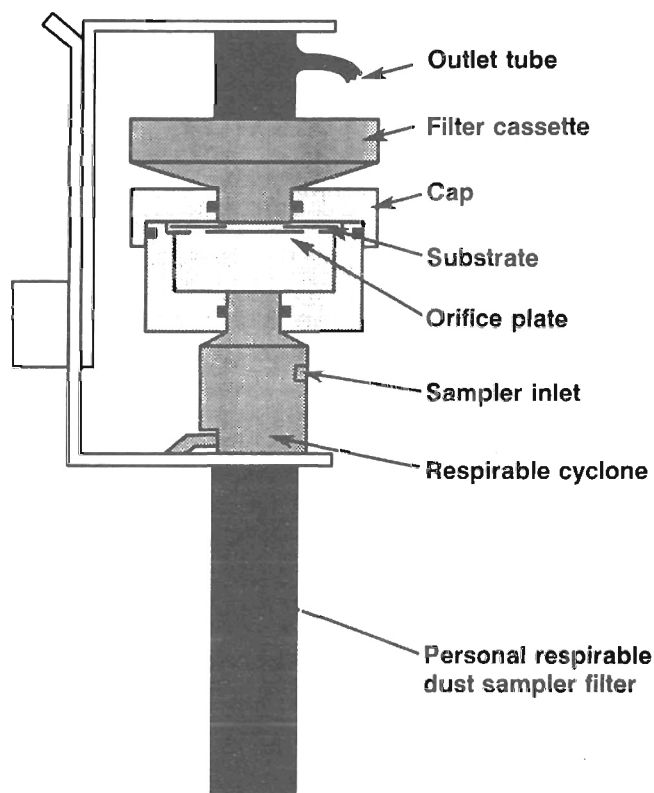


Figure 4.—Personal diesel exhaust aerosol sampler.

to interferences caused by submicron mineral dust and background atmospheric aerosol.

Both types of PDEAS were used to evaluate the filtration efficiency of the DDEF. Figure 5 shows the sampling stations used in the three entry longwall development sections of one of the mines in which the evaluation tests were performed. Up to 35 PDEAS samples were collected during each normal production shift in the ventilation intake entry (I), haulageway entry (H), on the diesel shuttle cars (SC), in the return air entry (R) and, in a few instances, individuals. Ventilation in the section is indicated by arrows.

In addition to the PDEAS samples, aerosol size distribution samples were collected in mines M and S using a 10-stage micro-orifice, uniform deposit impactor (MOUDI) (13). The analyses of MOUDI-derived size distributions provided accurate concentrations of DEA and respirable coal mine dust aerosol and were also used to evaluate the performance of the PDEAS.

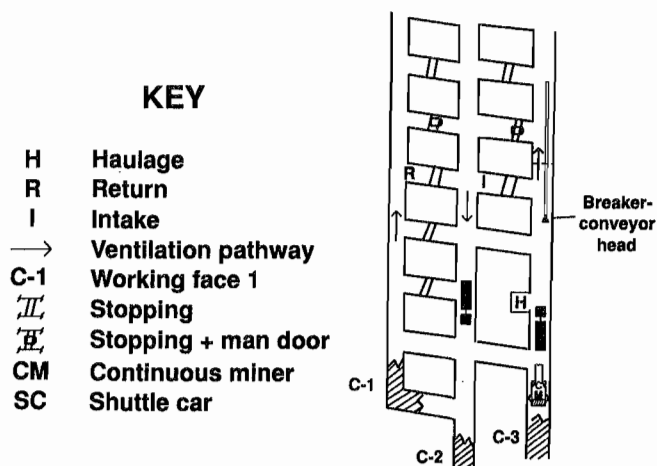


Figure 5.—Organization of typical continuous miner section.

## RESULTS AND DISCUSSION

Table 1 summarizes the PDEAS results of aerosol measurements taken with and without filters installed.

The table also indicates the reduction of DEA in the mine environment.

Table 1.—Diesel aerosol concentrations measured using the PDEAS with and without the DDEF

Location	DDEF installed				DDEF not installed				Reduction, <sup>1</sup> pt	
	Samples	Conc, mg/m <sup>3</sup>		$\delta$	Samples	Conc, mg/m <sup>3</sup>		$\delta$	Mean	SD
		Mean	SD			Mean	SD			
Mine M										
Intake . . . . .	3	0.06	0.02	1.00	1	0.06	<sup>2</sup> 0.02	1.16	NAp	NAp
Haulage . . . . .	7	0.12	0.02	0.90	2	0.50	0.02	1.63	94	6
Return . . . . .	20	0.09	0.03	0.89	5	0.80	0.03	1.63	98	4
Shuttle car . . . . .	8	0.17	0.05	0.84	2	0.81	0.03	1.63	93	7
Supervisor . . . . .	2	0.13	0.02	1.01	1	0.48	0.02	1.63	90	8
Personnel . . . . .	2	0.09	0.02	0.67	1	0.46	0.02	1.63	100	5
Mine R										
Intake . . . . .	16	0.05	0.03	1.03	14	0.04	0.03	0.93	NAp	NAp
Shuttle car . . . . .	56	0.28	0.07	1.00	39	0.83	0.17	1.02	71	7
Return . . . . .	10	0.29	0.05	0.96	7	0.82	0.06	1.12	73	2
Mine S										
Intake . . . . .	8	0.05	0.02	0.97	4	0.06	0.02	0.92	NAp	NAp
Shuttle car . . . . .	41	0.23	0.05	1.02	29	1.74	0.48	0.92	88	1
Haulage . . . . .	13	0.16	0.04	0.93	9	0.95	0.29	1.03	90	7
Return . . . . .	12	0.30	0.03	0.99	9	1.56	0.24	0.95	84	4

Conc Concentration.

DDEF Disposable diesel exhaust filter.

NAP Not applicable.

<sup>1</sup>Corrected for intake concentration, ventilation, and production changes.

<sup>2</sup>Standard deviation for a single sample is assumed to be the same as for a multiple sample.

PDEAS Personal diesel exhaust aerosol sampler.

SD Standard deviation.

$\delta$  Net correction factor.

DEA concentrations with the DDEF installed were less than or equal to 0.3 mg/m<sup>3</sup> at all locations. The concentrations and standard deviations shown in table 1 are average values uncorrected for intake air concentration or production and ventilation changes. However, the DEA reductions shown in the table were calculated by including correction factors for these parameters. The equation used to calculate the percent reductions,  $\Delta$ , is

$$\Delta = 100 \left[ 1 - \frac{C_w}{C_{w/o}} \right]$$

Here,  $C_w$  and  $C_{w/o}$  are the intake corrected average DEA concentrations measured with and without the DDEF in place; corrected for ventilation, section production, and aerosol background concentration in the intake air. They are calculated using:

$$C = \frac{1}{n} \sum_n [C_m \delta_m - C_I \delta_I]_n$$

Here,  $C$  is the intake corrected average concentration,  $C_m$  is the average measured concentration for day  $n$ ,  $\delta_m$  is the correction factor for the measured concentration, and  $C_I \delta_I$  is the average aerosol concentration measured in the section intake and its correction factor, respectively. The correction factors are determined from production tonnage and measured ventilation rates by:

$$\delta_m = \frac{\bar{P}}{P_m} \frac{V_m}{\bar{V}},$$

$$\delta_I = \frac{V_I}{\bar{V}}.$$

Here,  $P$  and  $P_m$  are the average production tonnage for the days during which the measured condition pertains, i.e., with or without filter, and the production tonnage for the shift of the measured concentration  $C_m$ . Similarly,  $V$  and  $V_x$  are the average ventilation rate for the shift during which the measured condition pertains and the ventilation rate at the location and on the day for the measured concentration  $C_x$ . The production correction only applies to the concentrations measured on the section. Also, since daily measured concentrations are not given in the table, a net correction factor is determined from the average measured and corrected values for the diesel aerosol concentrations and is reported in the table as an indication of the size of the corrections made.

These analyses indicate that the DDEF reduced DEA concentrations in the mine atmosphere by 95 pct with a standard deviation of 6 pct at mine M, 72 pct with a standard deviation of 4.5 pct at mine R, and 87 pct with a standard deviation of 4 pct at mine S.

Figures 6 and 7 show the size distribution of mine aerosol for mines M and S with and without the DDEF. These figures are based on data collected from the MOUDIs located at the haulage site. They effectively illustrate two points. (1) The DDEF is effective at removing most of the submicron aerosol from the mine atmosphere and (2) most submicron aerosol is attributable to diesel exhaust.

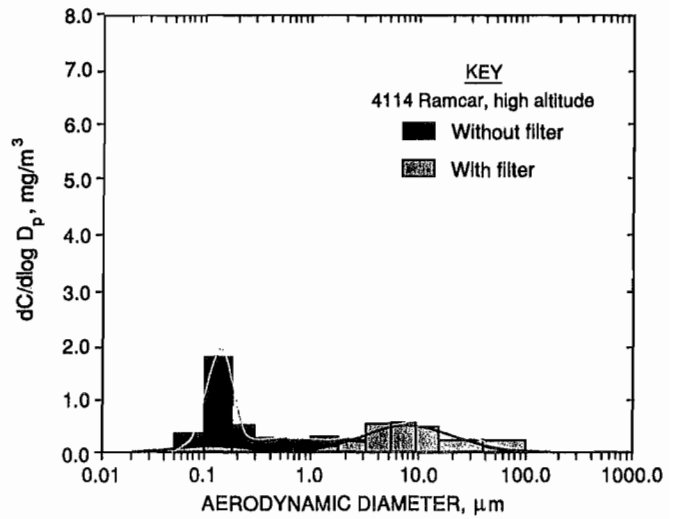


Figure 6.—Size distribution of diesel exhaust aerosol with and without disposable diesel exhaust mine filter at mine M.

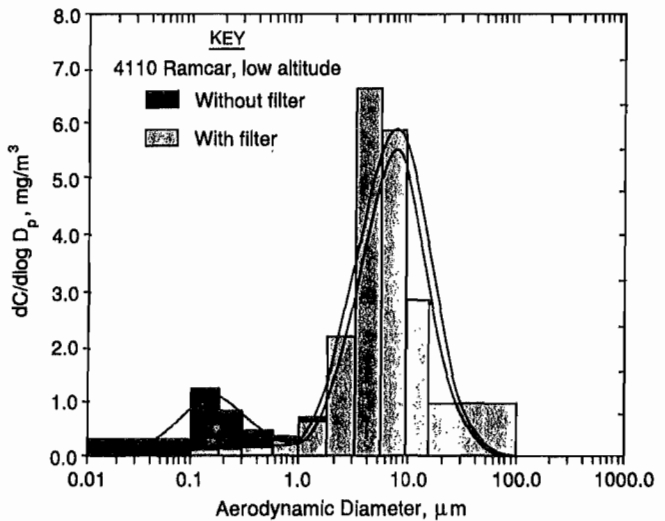


Figure 7.—Size distribution of diesel exhaust aerosol with and without disposable diesel exhaust mine filter at mine R.

## FACTORS AFFECTING FILTER LIFE

The useful service life of a DDEF is determined by the engine manufacturer's allowable exhaust backpressure limit. The maximum backpressure specified for the Caterpillar 3306 engine is 86 cm (34 in) of water. For the MWM 916-6 engine the maximum specified backpressure is 102 cm (40 in) of water. The exhaust backpressure is determined by summing the pressure drops across the waterbath scrubber, exhaust piping, and the filter. Measurements on DDEF systems, which were used during this testing, showed that the maximum backpressure imposed by the waterbath scrubber and exhaust system was approximately 25 cm (10 in) of water, so when the pressure drop across the filter reached 61 cm (24 in) of water, for the CAT 3306, or 76 cm (30 in) of water for the MWM 916-6, the filter required replacement.

The major factor affecting filter life on a waterbath scrubber equipped vehicle is the amount of DEA generated by the engine, which is dependent on such factors as the vehicle's duty cycle, engine type and condition, and mine altitude. During the field evaluations, the DDEF lasted up to 10 h on the Jeffrey 4114 Ramcar, and up to 32 h on the 4110 Ramcar.

Another consideration affecting filter life is water saturation. Owing to space limitations, the water trap was not sized to handle the excessive amount of water expelled from an overfilled waterbath scrubber upon starting the engine. Thus, a significant amount of water may pass into the filter canister, saturating the filter when the system is overfilled. The simplest solutions to this problem are to avoid overfilling waterbath scrubber, or to postpone installing the filter until after waterbath scrubber maintenance and initial engine startup.

## SUMMARY

The DDEF was evaluated at three underground coal mines using diesel equipment. It was shown to reduce in-mine DEA levels from 70 to 95 pct with a DDEF life of 10 to 32 h, depending on the application. The DDEF is widely accepted by the underground coal mining industry, with over 100 units ordered. Jeffrey Division, Dresser Industries, Inc., has MSHA-approved systems available for their 4110 and 4114 Ramcars, and Wagner Mining and Construction Equipment Co. has MSHA-approved available for a number of their permissible mining machines as well.

It is important that all safety systems, MSHA-mandated and those designed into the filter systems, be installed and maintained in peak operating conditions whenever filters are used on any vehicle in underground mines. Because of the potential fire hazards of using DDEFs on vehicles

## SAFETY CONCERNS

Jeffrey received MSHA approval to use the retrofit DDEF system on both the 4110 and 4114 Ramcars. Mine operators have reported some problems with vehicles equipped with DDEF systems. Under certain circumstances, the exhaust temperature will significantly exceed the recommended 95° C maximum for the filter. This condition results when the waterbath safety shutdown system malfunctions or is bypassed. The excessive temperature may cause ignition of the filter and collected diesel particulate. To avoid this problem, it is important to maintain the vehicle's safety systems in a permissible condition.

Direct contact with used DDEFs should be avoided if possible. Gloves should be worn during installation and removal to avoid contact with surfaces coated with soot and grease. The DDEFs should be bagged and brought to a disposal facility.

## AVAILABILITY AND COST

The prices for the 4110 and 4114 Ramcar retrofit DDEF systems are about \$3,800 and \$5,000, respectively, with a price of approximately \$40 per filter (15). Life expectancy of the filters is up to 10 hours on the 4114 Ramcar and up to 32 hours on the 4110 Ramcar.

Wagner Mining and Construction Equipment Co. has developed DDEF systems for some of their permissible mine equipment. These systems have been approved by MSHA and are available from Wagner. Wagner has indicated that the filters last 8 hours or more in the laboratory under full-load engine operating conditions. No system or filter cost is yet available.

with potentially high exhaust temperatures, it is imperative that the filter systems be properly engineered for the intended application and approved by MSHA before use in permissible equipment. The DDEF described here was designed to be used on diesel-powered vehicles equipped with exhaust cooling water scrubbers and is applicable only to those vehicles. Other solutions are necessary for vehicles not equipped with waterbath exhaust scrubbers.

Proper handling of the used filters is also important. Because of the health risks associated with exposure to diesel particulate, direct contact with used DDEFs should be avoided if possible. Gloves should be worn during installation and removal to avoid contact with surfaces coated with soot and grease. The DDEFs should be bagged and brought to a disposal facility.

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